Final Technical Report

21 June 2002

Local Tsunamis in Hawaii: Hazard Assessment and Emergency Response

NASA NAG5-8745

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Introduction

Dealing with local tsunami hazard in Hawaii presents formidable problems. Any earthquake larger than about magnitude 6.5, is potentially tsunamigenic. Because travel times are so short—a tsunami travels from Kona to Honolulu in only half an hour—warnings have to be made rapidly with incomplete data. But because evacuations themselves are hazardous, it is essential that the false alarm rate be kept low. Not only must those conflicting demands be dealt with, there is also the problem of deciding which areas to evacuate. Hawaii has tsunami evacuation maps for all coastlines, but those maps implicitly assume a distant source; locally-generated tsunamis were not been considered in the generation of the maps. This project, supported by the NASA Solid Earth and Natural Hazards Program, with additional support (via the State of Hawaii) from the NOAA National Tsunami Hazard Mitigation Program, was designed to address these problems.

Accomplishments

- Our techniques and source parameters were verified by simulating the Kalapana tsunami of 1975. In agreement with *Ma, et al.* [1999] (who looked only at tide gauge data), this study found that submarine displacements had to be much larger than the geodetically measured deformation at the coastline to satisfy the observed runups along the coast. We have accomplished a match to runup by including a slump component in the source.
- By applying the Kalapana source to the Kona (west) coast of the Big Island (Hawaii), and with appropriate scaling, a variety of Kona and South Kona events have been modeled. Potential tsunami sources have a continuum of severity from the $M_S = 6.9$ Kona earthquake of 1951, which produced such a small tsunami that only minor damage occurred along the immediate coast, to a massive sector collapse of Mauna Loa which would produce a Pacific-wide tsunami and severe destruction throughout the State of Hawaii. We limited modeling to sources small enough that they have at least a 10% probability of occurring within 50 years (a similar criterion is used for earthquake hazard assessment). With that criterion, the worst-case scenario for the State as a whole is a magnitude 7.4 earthquake, with an associated slump, in South Kona. This is essentially our Kalapana source doubled in size. Our earlier claim that tsunami size depends critically on location was flawed—the geometry of the Big Island does not permit the large variation in source location that we were modeling.
- From the results of our Kalapana and South Kona modeling, we worked in collaboration with the Pacific Tsunami Warning Center to recommend new warning procedures for local tsunamis. These recommendations are reproduced here as Appendix A. The recommendations were considered by emergency managers at their technical review meeting, July 13, 2001. County Civil Defense personnel discussed the warning-watch scheme proposed, but chose

not to follow it (preferring instead a single urgent tsunami warning). We are now (unfunded) drawing up criteria for local warnings based on new State of Hawaii runup sensors along the coast of the Big Island.

- Test inundation modeling has been performed for the south Oahu coast from Diamond Head to Ewa. A detailed inundation map for downtown Honolulu has been extracted from that modeling and is reproduced here as Appendix B. The map has been presented to emergency managers for comments on usefulness and presentation.
- Because people in Hawaii, especially teachers, are interested in this work, the above findings are reported on the web at www.soest.hawaii.edu/tsunami/. The work was also showcased (through animations and inundation maps) at the Bishop Museum's *X-treme Science* exhibition from Jan. 27 to May 28, 2001.

Status of Deliverables: Failure of Traditional Tsunami Models

Early in the tenure of this project, we visited the Pacific Disaster Center and offered to install our version of the Imamura code TUNAMI-N2, and the evolving Hawaiian Islands bathymetry data set. Together, these entities comprise the local tsunami model. Once PDC learned that the model was impractical for real-time use (because warning times are 30 minutes or less), and that inundation would have to be pre-computed from all hypothesized sources, they chose instead to defer installation until the model was finalized and we could provide a master suite of inundation computations. For reasons we explain here, that finalization has yet to occur.

The project initially fell behind schedule because of delay and errors in processing SHOALS data (shallow water bathymetry of the Scanning Hydrographic Operational Airborne Lidar Survey) by consultants processing data for the Army Corps of Engineers. That delay, however, allowed us to scrutinize the modeling results made with more approximate bathymetry. We discovered major problems.

Most tsunami inundation mapping, including both our work using Imamura's code TUNAMI-N2 and the PMEL/USC MOST model, simulate tsunamis not just by assuming that wavelengths are very long compared to ocean depths, but also by considering only depth-averaged quantities. Such models are adequate for long-period tsunamis generated by distant earthquakes. The period of locally-generated tsunamis in Hawaii, however, is dominated by the reflection of waves off a nearby coast. Rather than the15-to-60 minute period of classical tsunamis, the period can fall to as little as six minutes. At such short periods, the long-wavelength approximation's implicit assumption of no dispersion breaks down (for the 4500 m abyssal depths around Hawaii, dispersion becomes serious for periods shorter than about 9 minutes). Further, the shorter periods mean steeper wave faces, for which the other assumption, that particle velocity can be replaced by its average over depth, also breaks down. These failures of the underlying theory first manifest themselves in our Honolulu inundation modeling—behavior was normal for 15-minute waves, but as we shortened wave period, inundation looked less and less physical until, for 6-minute waves, water flowed onto the land but did not flow off.

The explanation of the Honolulu modeling result is simple. In a steepening wave front, as in a tsunami approaching shore, momentum is carried progressively higher and higher in a wave (i.e., the crest moves faster than the trough). By assuming constant velocity with depth, conservation of momentum forces the inundating wave to become a thin, high-velocity jet, which suppresses backflow. While such behavior is implicit in all tsunami modeling made by solving the depth-averaged shallow-water equations, it only becomes egregiously non-physical for waves with periods shorter than ten minutes. We will submit a paper on this problem in the near future.

The modeling inadequacies are especially acute for edge waves—waves trapped along a shoreline. One of the big surprises of this work was the hazard tsunamis from South Kona pose to the Kihei coast of Maui. The modeling shows that energy is trapped between the coasts of Maui, Lanai, and Molokai, but much of that energy propagates as edge waves. With TUNAMI-N2, such waves do appear, but their propagation is not correctly modeled. Generating inundation maps for the heavily populated south coast of Maui is now an urgent priority, but with our existing tools we cannot adequately accomplish such mapping.

Current and Future Directions

It is clear that assessing local tsunami hazard in the Hawaiian Islands will require more sophisticated modeling than the shallow-water approximation provides. Since our original SENH program was for an application rather than research and development, it was inappropriate to request support for code development under the November 2001 Research Announcement (the necessary SHOALS data were still unavailable anyway). We did not therefore submit a new proposal. Nevertheless, because of the clear need, we are now (without funding) adapting the fourth-order Boussinesq code GEOWAVE, developed by Applied Fluids Engineering from James Kirby's shoreline inundation code FUNWAVE, to the Hawaiian application. GEOWAVE avoids the major shortcomings of TUNAMI-N2, but demands substantially more computer time; we shall port it to the Linux cluster at the Maui High-Performance Computing Center. GEOWAVE is still in the beta-test stage, but once it is stable we shall offer the model to PDC.

Publications and Presentations Supported by this Project

Fryer, G., and C. McCreery, 2001. Warning Procedures for Tsunamis Generated Within the Hawaiian Islands: Recommendations, *Tsunami Technical Review Committee, State of Hawaii Civil Defense*, 13 July 2001. (reproduced here as Appendix A).

Fryer, G.J., J.R. Smith, Jr., and P. Watts, Tsunami inundation limits for a locally-generated tsunami from the Kona Coast, Map 1. Honolulu, Prerelease version 0.2, *Tsunami Technical Review Committee, State of Hawaii Civil Defense*, 17 December 2001. (reproduced here as Appendix B).

Watts, P., and G.J. Fryer, 2002. Approximations and their consequences in tsunami inundation mapping, *Natural Hazards*, in preparation.

APPENDIX A

Warning Procedures for Tsunamis Generated Within the Hawaiian Islands: Recommendations

by

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Charles McCreery, *Pacific Tsunami Warning Center*
July 13, 2001

Existing policy:

For any earthquake with magnitude greater than 6.8 an Urgent Local Tsunami Warning is issued for the county in which the earthquake occurred and for adjacent counties. No Watch or Warning is issued for other counties. The Warning is upgraded to a statewide Warning if a significant tsunami is observed outside the county in which the earthquake occurred.

Recommended policy:

1. For any earthquake with a magnitude greater than 6.8, if its epicenter occurs offshore or onshore within ten miles of the shoreline, an Urgent Local Tsunami Warning will be issued for the entire county in which the earthquake occurs.
2. If the earthquake epicenter is west of Ka Lae (South Point) and south of Keahole Point, a Local Tsunami Watch will be issued for Maui, Honolulu, and Kauai Counties. The Watch will either be cancelled or upgraded to an Urgent Local Tsunami Warning based on data from the nearest sea level and runup gauges. These data should be available within about 15 minutes of the earthquake.
3. If the earthquake epicenter is on the southeast shore of the Big Island between Ka Lae (South Point) and Cape Kumukahi and within 10 miles of the shoreline or anywhere offshore, a tsunami watch should be issued for eastern Maui (within ten miles of Hana). The Watch will either be cancelled or upgraded to an Urgent Local Tsunami Warning based on data from the nearest sea level and runup gauges. These data should be available within about 15 minutes of the earthquake.

Explanations:

1. For the Big Island, the coastline in the vicinity of a large earthquake will be hit by a tsunami, if one is going to occur, in 3-10 minutes. The shaking itself must be the tsunami warning. The Urgent Local Tsunami Warning will provide warning for the rest of the island.
2. For earthquakes in North Kona or South Kona, water-level gauges in Milolii and Honokohau will detect any tsunami. Both installations are robust and have direct VHF communications with Haleakala. They can therefore be expected to remain operational through a severe earthquake. Depending on the exact location of the earthquake, these gauges will see an initial drawdown 3-7 minutes after the earthquake, with a positive wave cresting

about three minutes later (the Honokohau gauge might be delayed a minute or two, especially for a small tsunami, because of the bottleneck of the harbor entrance). If wave heights in excess of 3 meters are recorded at both gauges, or if other equivalent evidence of large waves is received, the Warning will be extended to the rest of the State.

3. For earthquakes in Ka'u or Puna, any tsunami will be recorded by water-level gauges at Honuapo and Kapoho. The Honuapo gauge depends on microwave communications to the Hawaiian Volcano Observatory. Because microwave communications require well-aligned antennas, and because tsunami-generating earthquakes in this region have a history of very strong ground acceleration, it is possible that communications will be disrupted and the Honuapo data will not be available. The Kapoho gauge, however, uses VHF communications to Hilo, and is more likely to remain operational. If both Honuapo and Kapoho gauges record wave heights of 3 meters or more, or if other equivalent evidence for large waves is received, the tsunami warning will be issued for Hana, Maui.

These criteria represent out best effort at a rational warning policy based on existing information. As more information becomes available, from modeling or elsewhere, and as more real-time data feeds become available (such as Dr. Walker's run-up gauges), these criteria should be refined.

Matters for discussion

1. The north shores of Maui, Molokai, Oahu, and Kauai will remain unaffected by a Big Island tsunami. Why bother to include them in any warning?
2. For a Ka'u-Puna event, the only part of Maui County affected is Hana. Why bother with the rest of the county?
3. Deep offshore earthquakes up the chain from the Big Island, most notably the 1871 Lanai earthquake, and the 1938 Maui earthquake, do not generate tsunamis. How should such events be handled?

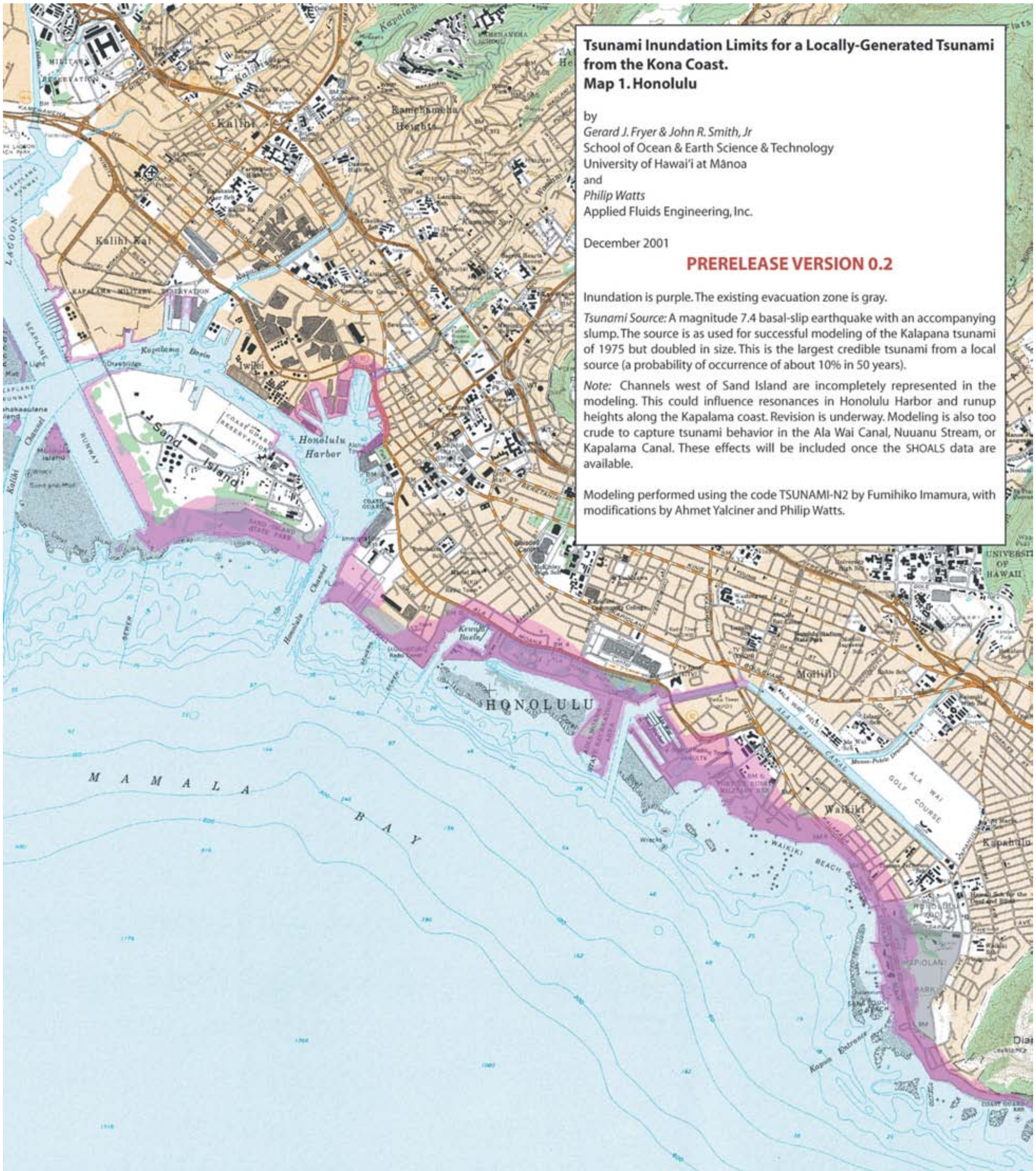
Outstanding issues to be resolved by further modeling

1. Lanai. Lanai is a special case as it seems likely to suffer extreme runup (at both Manele Bay and Kaumalapau Harbor) during a tsunami from the Kona Coast. More modeling runs should be performed to determined appropriate warning thresholds.
2. Kauai. The only coastline of Kauai likely to be at hazard is the western shore facing Niihau (from Waimea to Barking Sands). Again, more modeling should determine the warning thresholds.
3. South Maui. Because the sea floor off the south coast of Maui is so shallow, it is possible that the wave heights we have computed are underestimates. Inundation mapping will solve this problem.

The most urgent need

Education!

APPENDIX B



Tsunami Inundation Limits for a Locally-Generated Tsunami from the Kona Coast.
Map 1. Honolulu
by
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and
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Applied Fluids Engineering, Inc.
December 2001
PRERELEASE VERSION 0.2
Inundation is purple. The existing evacuation zone is gray.
Tsunami Source: A magnitude 7.4 basal-slip earthquake with an accompanying slump. The source is as used for successful modeling of the Kalapana tsunami of 1975 but doubled in size. This is the largest credible tsunami from a local source (a probability of occurrence of about 10% in 50 years).
Note: Channels west of Sand Island are incompletely represented in the modeling. This could influence resonances in Honolulu Harbor and runup heights along the Kapalama coast. Revision is underway. Modeling is also too crude to capture tsunami behavior in the Ala Wai Canal, Nuuanu Stream, or Kapalama Canal. These effects will be included once the SHOALS data are available.
Modeling performed using the code TSUNAMI-N2 by Fumihiko Imamura, with modifications by Ahmet Yalciner and Philip Watts.
HONOLULU
MAMALA BAY
Sand Island
Honolulu Harbor
Waikiki